

Energy Efficiency Analysis in Amplify-and-Forward and Decode-and-Forward Cooperative Networks

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Abstract—¹ In this paper, we have studied the energy efficiency of cooperative networks operating in either the fixed Amplify-and-Forward (AF) or the selective Decode-and-Forward (DF) mode. We consider the optimization of the M -ary quadrature amplitude modulation (MQAM) constellation size to minimize the bit energy consumption under given bit error rate (BER) constraints. In the computation of the energy expenditure, the circuit, transmission, and retransmission energies are taken into account. The link reliabilities and retransmission probabilities are determined through the outage probabilities under the Rayleigh fading assumption. Several interesting observations with practical implications are made. For instance, it is seen that while large constellations are preferred at small transmission distances, constellation size should be decreased as the distance increases. Moreover, the cooperative gain is computed to compare direct transmission and cooperative transmission.

I. INTRODUCTION

In wireless networks, the introduction of relaying provides higher link reliability when the source-destination link suffers severe fading. Among different cooperative strategies, the fixed (AF) and the selective (DF) cooperative techniques are often employed in cooperative networks. In the fixed AF, the relay doesn't perform decoding on received signals and always forwards the amplified received signals to the destination. The selective DF model differs from the fixed AF in that it will perform Decode-and-Forward only if its received signal-to-noise ratio (SNR) $\gamma_{s,r}$ from the source is greater than a threshold γ_{th} . By comparison, the fixed AF is easy to implement while the selective DF may be more complicated on hardware but performs better in terms of bandwidth efficiency. In this paper, we consider both models and propose maximum ratio combining (MRC) and non-MRC decoding at the destination and analyze their energy efficiencies.

Several previous studies in which energy or power efficiency of cooperative transmissions is considered either opt to minimize the total power when constrained by a given system outage probability, or maximize the network lifetime with some instantaneous power constraints [1], [2], [3]. However, specific modulations schemes or link layer retransmissions have not been considered and incorporated in the analysis in such studies. Since the modulation size affects the transmission rate and consequently the transmission time, it certainly has a significant impact on the total energy consumption. When modulation schemes are explicitly considered, power

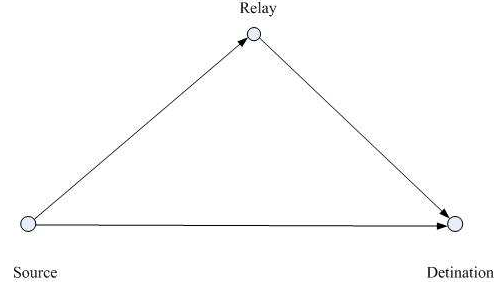


Fig. 1. One-Relay Cooperative Model

consumption normalized by the transmission rate, i.e., energy per bit, rather than total power consumption should be used in order to provide fair comparison between different modulation schemes. In addition, energy expended in retransmissions, together with circuit energy consumption, should be included in the energy efficiency analysis for more accurate results.

In this paper, motivated by these considerations, we investigate the energy efficiency of cooperative transmissions by jointly considering transmission, circuit, and retransmission energies, and analyzing the bit energy levels achieved by different MQAM schemes. In the system model, we assume a Rayleigh fading channel, through which the source sends information packets to the destination and relay by broadcasting. Constrained by a given BER requirement, we derive the system outage probability. The relay is assumed to assist the transmission to the destination in either the AF or DF modes, with or without MRC. Different MQAM sizes are investigated to find the optimal constellation size in terms of minimum bit energy consumption.

II. SYSTEM FORMULATION AND CHANNEL ASSUMPTIONS

We assume a 3-node cooperative network, where the source has a certain number of bits to transmit to the destination. While the relay is initially assumed to be located in the middle between the source and destination, the performance at different locations are analyzed subsequently. The broadcast from the source can be heard by the relay and destination. When the destination successfully receives the signals either from the source or from the relay's cooperative transmission, it sends Acknowledgement back to the source to indicate a successful transmission. Otherwise, the source will retransmit until a successful packet delivery is achieved at the destination. We assume 3 independent Rayleigh fading channels for the

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source-destination (S-D) link, the source-relay (S-R) link and the relay-destination (R-D) link. Moreover, white Gaussian noise with zero mean and variance N_0 is assumed to be added to the received signals at receivers.

A. Cooperative Network Model

Figure 1 shows the system model. The introduction of a relay node definitely adds more energy overhead and system complexity, but it creates more reliability from the auxiliary R-D link when S-D channel fails. If we assume the signal transmitted from the source is x with unit energy and gets broadcasted through the combined path loss and Rayleigh fading channels, the received signals at the relay and destination can be represented by

$$y_{s,r} = \sqrt{P_t d_{s,r}^{-\beta}} h_{s,r} x + n_{s,r} \quad (1)$$

$$y_{s,d} = \sqrt{P_t d_{s,d}^{-\beta}} h_{s,d} x + n_{s,d} \quad (2)$$

where P_t is the transmit power of the source. In the above formulation, $d_{s,r}^{-\beta}$ and $d_{s,d}^{-\beta}$ denote the path loss components as functions of the S-D distance $d_{s,d}$, the S-R distance $d_{s,r}$ and the path loss exponent β . $h_{s,r}$ and $h_{s,d}$ are channel fading coefficients between S-R and S-D, respectively, modeled as zero-mean circularly symmetric Gaussian complex random variables. $n_{s,d}$ and $n_{s,r}$ are the additive Gaussian noise at the destination and relay, respectively.

B. Circuit and Transmission Energies

We adopt the accurate energy consumption formulation from [4], by assuming the source has L bits to transmit directly to the destination. Such a single transmission consists of 2 distinct periods: transmission period T_{on} and transient period T_{tr} . Accordingly, the total energy required to send 1 bit is represented by

$$E_a = (((1 + \alpha)P_t + P_{ct} + P_{cr})T_{on} + P_{tr}T_{tr})/L \quad (3)$$

where $P_{on} = (1 + \alpha)P_t + P_{ct} + P_{cr}$.

Specifically, P_{on} comprises the transmit power P_t , the amplifier power αP_t , the circuit power P_{ct} at the source transmitter and P_{cr} at the destination receiver and the transient power P_{tr} .

We consider uncoded square MQAM as our modulation and have

$$T_{on} = \frac{LT_s}{b} = \frac{L}{bB} \quad (4)$$

where b is the constellation size defined as $b = \log_2 M$ in MQAM, and T_s is the symbol duration approximated by $T_s \approx 1/B$. Finally, the amplifier efficiency for MQAM can be obtained from $\alpha = \frac{\xi}{\eta} - 1$ where $\xi = 3\frac{\sqrt{M}-1}{\sqrt{M}+1}$ in [5].

C. BER Constraint for MQAM

In our model, QoS is constrained by a given BER on each transmission link and P_t is specified. In an uncoded square MQAM, we can derive the SNR γ_b according to a given p_b in the AWGN channel, according to (5) below:

$$p_b = \frac{1 - (1 - \frac{2(\sqrt{M}-1)}{\sqrt{M}}Q(\sqrt{\frac{3b\gamma_b}{M-1}}))^2}{b} \quad (5)$$

The SNR threshold in our model is therefore derived as

$$\gamma_{th} = \frac{P}{N_0} = \frac{E_b}{N_0 T_b} = \gamma_b \log_2^M B. \quad (6)$$

With γ_{th} , we can compute the system outage probability in the following sections.

III. ONE-RELAY AF COOPERATIVE MODEL WITH/WITHOUT MRC

In fixed AF, network can have 2 different states: in state 1, the source broadcasts the signal x and the received signals at the relay and destination can be represented by (1) and (2). At the end of state 1, the destination will first attempt to decode $y_{s,d}$ to see if it has been received correctly; otherwise the network will initiate state 2 in which the relay helps to forward $y_{s,r}$ to the destination by scaling it with θ_r

$$\theta_r = \frac{1}{\sqrt{P_t d_{s,r}^{-\beta} |h_{s,r}|^2 + N_0}} \quad (7)$$

and then transmitting this scaled signal with power P_t to the destination. So, the received signal from the relay at the destination is

$$y_{r,d} = \frac{\sqrt{P_t d_{r,d}^{-\beta}}}{\sqrt{P_t d_{s,r}^{-\beta} |h_{s,r}|^2 + N_0}} h_{r,d} \sqrt{P_t d_{s,r}^{-\beta}} h_{s,r} x + n'_{r,d}. \quad (8)$$

The noise term in (8) is

$$n'_{r,d} = \frac{\sqrt{P_t d_{r,d}^{-\beta}}}{\sqrt{P_t d_{s,r}^{-\beta} |h_{s,r}|^2 + N_0}} h_{r,d} n_{s,r} + n_{r,d} \quad (9)$$

with variance

$$N'_0 = \left(\frac{P_t d_{r,d}^{-\beta} |h_{r,d}|^2}{P_t d_{s,r}^{-\beta} |h_{s,r}|^2 + N_0} + 1 \right) N_0. \quad (10)$$

A. Fixed AF without MRC

We first study the fixed AF without MRC, where the destination only utilizes $y_{r,d}$ from the relay for decoding if the S-D link has failed. After state 2, if the destination still fails to correctly receive the signal, it then notifies the source to schedule a retransmission, and this repeats until a successful signal delivery is achieved at the destination. The successful signal reception statistically depends on the outage probability of the direct S-D link and the cooperative S-R-D link. If we assume $|h_{s,r}|^2$, $|h_{s,d}|^2$, and $|h_{r,d}|^2$ are exponentially distributed with unit mean, then $\gamma_{s,d}$, which is defined as,

$$\gamma_{s,d} = \frac{P_t d_{s,d}^{-\beta} |h_{s,d}|^2}{N_0}, \quad (11)$$

has an exponential distribution with cumulative density function (CDF) evaluated at γ_{th} given by

$$p(\gamma_{s,d} \leq \gamma_{th}) = 1 - e^{-\frac{N_0 d_{s,d}^{-\beta} \gamma_{th}}{P_t}}. \quad (12)$$

The received SNR $\gamma_{r,d}$ at the destination from the relay is more complicated and represented by

$$\gamma_{r,d} = \frac{(\frac{P_t d_{s,r}^{-\beta}}{N_0})|h_{s,r}|^2 (\frac{P_t d_{r,d}^{-\beta}}{N_0})|h_{r,d}|^2}{(\frac{P_t d_{s,r}^{-\beta}}{N_0})|h_{s,r}|^2 + (\frac{P_t d_{r,d}^{-\beta}}{N_0})|h_{r,d}|^2 + 1} \quad (13)$$

and its CDF is formulated as (see e.g., [6] and [7])

$$p(\gamma_{r,d} \leq \gamma_{th}) = 1 - \sqrt{\xi} e^{-\gamma_{th}(\frac{N_0}{P_t d_{s,r}^{-\beta}} + \frac{N_0}{P_t d_{r,d}^{-\beta}})} K_1(\sqrt{\xi}) \quad (14)$$

where $\xi = \frac{4(\gamma_{th}^2 + \gamma_{th})N_0^2}{P_t^2 d_{s,r}^{-\beta} d_{r,d}^{-\beta}}$ and $K_1()$ is the first order modified Bessel function of the second kind. The system success probability is therefore derived as

$$p_{success1} = 1 - p_{out} = 1 - p(\gamma_{s,d} \leq \gamma_{th})p(\gamma_{r,d} \leq \gamma_{th}).$$

With γ_{th} derived in Section II, the number of retransmissions is a geometric random variable and has a mean of $\frac{1}{p_{success1}}$ [8]. We then formulate the system average power consumption from

$$P_{avg1} = ((1 + \alpha)P_t + P_{ct} + 2P_{cr})p(\gamma_{s,d} \geq \gamma_{th}) + (2(1 + \alpha)P_t + 2P_{ct} + 3P_{cr})p(\gamma_{s,d} \leq \gamma_{th}) \quad (15)$$

where the power in the first term corresponds to the total consumption in state 1 where the S-D link is not in outage; the second term corresponds to both state 1 and state 2 when S-D link is in outage and the relay participates to transmit the received signal to the destination. Considering retransmission, the average bit energy consumption is

$$E_{a1} = \frac{P_{avg1}T_{on} + P_{tr}T_{tr}}{Lp_{success1}}. \quad (16)$$

To measure how much energy efficiency can be achieved from cooperative transmission, we define the cooperative gain as

$$gain_1 = \frac{E_{direct}}{E_{a1}} \quad (17)$$

where

$$E_{direct} = \frac{E_a}{p(\gamma_{sd} \geq \gamma_{th})}. \quad (18)$$

B. Fixed AF with MRC

The fixed AF with MRC differs from the non-MRC scheme only in state 2: if the S-D link fails, the relay will amplify and forward its received signal to the destination and we suppose the destination employs a coherent detector which knows all channel fading coefficients $h_{s,d}$, $h_{s,r}$ and $h_{r,d}$, such that both $\gamma_{s,d}$ and $\gamma_{r,d}$ will be combined with MRC techniques to output the maximized equivalent SNR γ

$$\gamma = \gamma_{s,d} + \gamma_{r,d} \quad (19)$$

where $\gamma_{s,d}$ and $\gamma_{r,d}$ have been derived at (11) and (13).

If the destination still fails to correctly receive the signal in state 2, retransmission will be initiated until a successful signal delivery at the destination. Therefore, this system has a success probability given by

$$p_{success2} = 1 - p_{out} = 1 - p(\gamma_{s,d} \leq \gamma_{th})p(\gamma_{s,d} + \gamma_{r,d} \leq \gamma_{th}) \quad (20)$$

TABLE I
NETWORK AND CIRCUIT PARAMETERS

$\bar{p}_b = 10^{-4}$	$P_t = 100\text{mW}$
$N_0 = 10^{-14}\text{W/Hz}$	$\beta = 3.12$
$L = 20000$ bits	$freq = 2.5 * 10^9\text{Hz}$
$P_{tr} = 100\text{mW}$	$P_{ct} = 98.2\text{mW}$
$\eta = 0.35$	$P_{cr} = 112.5\text{mW}$
$B = 10\text{KHz}$	$T_{tr} = 5\mu s$

The CDF of $\gamma_{r,d}$ conditioned on $\gamma_{s,d}$ is

$$p(\gamma_{r,d} \leq \gamma_{th} - \gamma_{s,d} | \gamma_{s,d}) = 1 - \sqrt{\xi} e^{-(\gamma_{th} - \gamma_{s,d})(\frac{N_0}{P_t d_{s,r}^{-\beta}} + \frac{N_0}{P_t d_{r,d}^{-\beta}})} K_1(\sqrt{\xi}) \quad (21)$$

where

$$\xi = \frac{4((\gamma_{th} - \gamma_{s,d})^2 + (\gamma_{th} - \gamma_{s,d}))N_0^2}{P_t^2 d_{s,r}^{-\beta} d_{r,d}^{-\beta}}. \quad (22)$$

Then, we average it over $\gamma_{s,d}$ and derive

$$p(\gamma_{r,d} + \gamma_{s,d} \leq \gamma_{th}) = \int_0^{\gamma_{th}} p(\gamma_{r,d} \leq \gamma_{th} - \gamma_{s,d} | \gamma_{s,d}) f(\gamma_{s,d}) d\gamma_{s,d} \quad (23)$$

where

$$f(\gamma_{s,d}) = \frac{N_0}{P_t d_{s,d}^{-\beta}} e^{\frac{N_0}{P_t d_{s,d}^{-\beta}} \gamma_{s,d}}. \quad (24)$$

We can similarly calculate the average bit energy consumption E_{a2} and the cooperative gain₂ in the fixed AF with MRC similarly as in (16) and (17) in the AF without MRC.

C. Bit Energy Consumption and Cooperative Gain Analysis in AF

By using the parameters provided in Table I [4], [9], [10], we perform numerical computations on the above two models. The results are shown in the following figures, with solid-line curves corresponding to the MRC model and broken-line curves corresponding to the non-MRC model.

First in Fig. 2, we vary the constellation size $b \in [2, 4, 6, 8, 10]$ at a specific S-D distance $d \in [5m, 25m, 50m, 75m, 100m]$ to see how bit energy consumption changes. We immediately observe the following. At relatively large S-D distances in either MRC or non-MRC models, the bit energy increases as b gets either large or very small, and hence, there exists an optimal b that minimizes the bit energy. We have the following tradeoff. An MQAM with large b transmits signals at a faster rate and consequently decreases T_{on} and hence the energy consumption in a single transmission, but it also requires a higher γ_{th} , leading to higher outage probability and as a result more energy from retransmissions. A small constellation size requires more energy in a single transmission, but less retransmissions. Hence, the optimal constellation size exists to provide a balance between these effects. We also observe at any S-D distance that both models achieve the same optimal b and the energy-minimizing constellation size gets smaller with

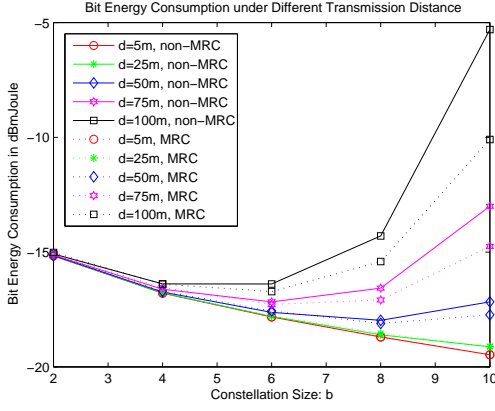


Fig. 2. Bit Energy Consumption vs Constellation Size in AF

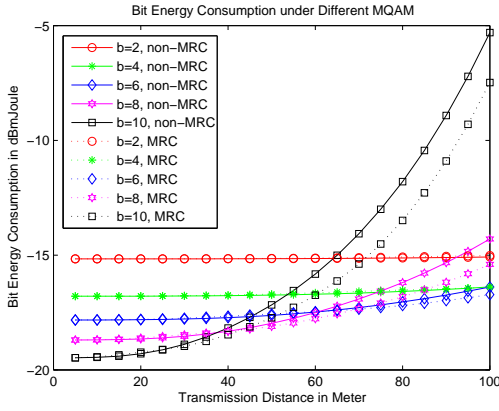


Fig. 3. Bit Energy Consumption vs S-D Distance in AF

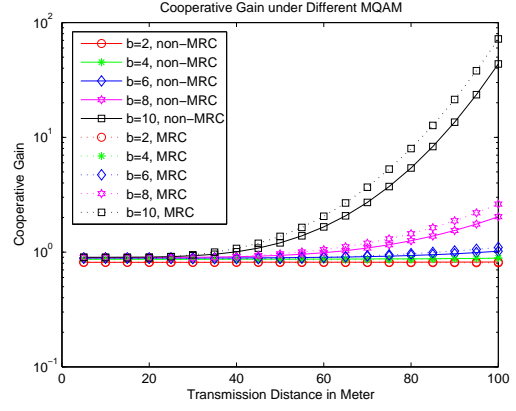


Fig. 4. Cooperative Gain vs S-D Distance in AF

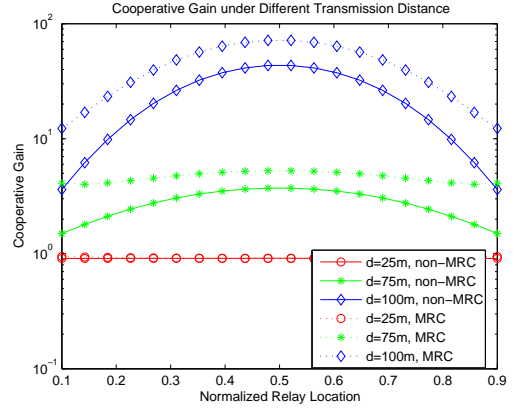


Fig. 5. Cooperative Gain vs Normalized Relay Location in AF

increasing S-D distance. However, at small distances such as 5m and 25m, whatever the constellation size is, the link reliability is always very high. So, large constellation size is always preferred because it consumes less energy in a single transmission.

It is immediately seen, as expected, that the MRC model outperforms the non-MRC model especially at large b and S-D distances. However, at small distances, these 2 models achieve almost the same performance. In such cases, simpler non-MRC techniques can be preferred.

In Fig. 3, the bit energy is plotted as a function of S-D distance at a specific $b \in [2, 4, 6, 8, 10]$. We see that while large constellation sizes are performing well at small distances, small constellations should be preferred when the distance gets large. Again, the MRC model outperforms the non-MRC model in terms of lower bit energy consumption.

In Fig. 4 in which cooperative gain is plotted, the MRC model again achieves higher gains. We also see when $b \leq 6$, the direct transmission is almost always more energy efficient than the cooperative transmission. But, the cooperative transmission starts outperforming the direct transmission at $b = 8$ when $d \geq 60m$ and at $b = 10$ when $d \geq 40m$. This is because at small distances, cooperation of the relay will increase the

energy overhead, counteracting its energy saving from added reliability and making it less efficient. On the other hand, at larger b and distances, the energy saving from less number of retransmissions by improved reliability dominates so that the system achieves very high cooperative gains.

Now, we fix $b = 10$ and move the location of the relay either closer to the source or closer to the destination, indicated by a normalized location index from 0.1 to 0.9, where 0.5 means the relay is located right in the middle, in order to see the impact on cooperative gain. In Fig. 5, when the S-D distance is 25m, both non-MRC and MRC achieve the same gain, almost always less than 1. At higher transmission distances such as 75m and 100m, very high gains show that the system significantly benefits from the cooperative transmission and MRC always outperforms non-MRC. Also, we observe that the maximal cooperative gain is achieved when the relay is located in exactly the middle of the source and the destination.

IV. ONE-RELAY DF COOPERATIVE MODEL WITH/WITHOUT MRC

In selective DF, the relay performs decode-and-forward only if $\gamma_{s,r} \geq \gamma_{th}$ while $\gamma_{s,d} \leq \gamma_{th}$. So, there are 4 mutually

exclusive working states in the DF: 1. S-D link successful; 2. both S-D link and S-R link in outage; 3. S-D link in outage, but S-R and R-D links successful; 4. S-D link and R-D in outage, but S-R link successful.

A. Selective DF without MRC

According to the above 4 different states, the system average power consumption can be formulated as

$$P_{avg3} = ((1 + \alpha)P_t + P_{ct} + 2P_{cr})p(\gamma_{s,d} \geq \gamma_{th}) + ((1 + \alpha)P_t + P_{ct} + 2P_{cr})p(\gamma_{s,d} \leq \gamma_{th})p(\gamma_{s,r} \leq \gamma_{th}) + (2(1 + \alpha)P_t + 2P_{ct} + 3P_{cr})p(\gamma_{s,d} \leq \gamma_{th})p(\gamma_{s,r} \geq \gamma_{th}). \quad (25)$$

The system success probability is defined as

$$p_{success3} = p(\gamma_{s,d} \geq \gamma_{th}) + p(\gamma_{s,d} < \gamma_{th})p(\gamma_{s,r} \geq \gamma_{th})p(\gamma_{r,d} \geq \gamma_{th}) \quad (26)$$

which can be calculated according to the following CDFs of exponential distribution

$$p(\gamma_{s,d} \leq \gamma_{th}) = 1 - e^{-\frac{N_0 d_{s,d}^\beta \gamma_{th}}{P_t}} \quad (27)$$

$$p(\gamma_{s,r} \leq \gamma_{th}) = 1 - e^{-\frac{N_0 d_{s,r}^\beta \gamma_{th}}{P_t}} \quad (28)$$

$$p(\gamma_{r,d} \leq \gamma_{th}) = 1 - e^{-\frac{N_0 d_{r,d}^\beta \gamma_{th}}{P_t}}. \quad (29)$$

Hence, the bit energy consumption in this model is

$$E_{a3} = \frac{P_{avg3}T_{on} + P_{tr}T_{tr}}{Lp_{success3}} \quad (30)$$

and the cooperative gain is

$$gain_3 = \frac{E_{direct}}{E_{a3}}. \quad (31)$$

B. Selective DF with MRC

In this model, since we assume the destination employs a coherent detector, MRC will output a combined $\gamma = \gamma_{s,d} + \gamma_{r,d}$. The network will have the same 4 working states as the non-MRC DF model with an average power

$$P_{avg4} = P_{avg3}. \quad (32)$$

The system success probability is defined as

$$p_{success4} = p(\gamma_{s,d} \geq \gamma_{th}) + p(\gamma_{s,d} < \gamma_{th})p(\gamma_{s,r} \geq \gamma_{th})p(\gamma_{s,d} + \gamma_{r,d} \geq \gamma_{th}). \quad (33)$$

We know the combined SNR of two independent exponential random variables $\gamma_{s,d}$ and $\gamma_{r,d}$ has the following distribution

$$f_z(z) = \int_0^z f_x(x)f_y(z-x)dx \quad z > 0 \\ = \frac{\lambda_a \lambda_b}{\lambda_b - \lambda_a} [e^{-\lambda_a z} - e^{-\lambda_b z}] \quad (34)$$

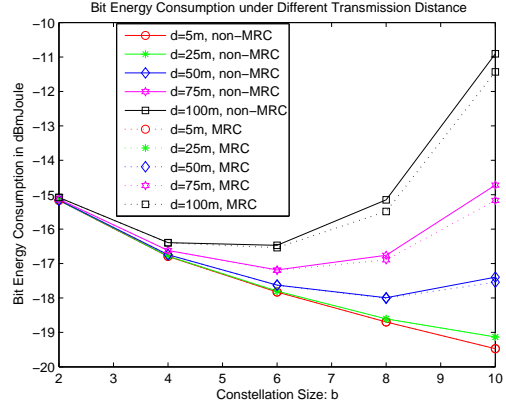


Fig. 6. Bit Energy Consumption vs Constellation Size in DF

where $\frac{1}{\lambda_a} = \frac{P_t}{N_0 d_{s,d}^\beta}$ is the mean of $\gamma_{s,d}$ and $\frac{1}{\lambda_b} = \frac{P_t}{N_0 d_{r,d}^\beta}$ is the mean of $\gamma_{r,d}$. Therefore, we have

$$p(\gamma_{s,d} + \gamma_{r,d} \geq \gamma_{th}) = 1 - \int_0^{\gamma_{th}} f_z(z)dz \\ = \frac{\lambda_b e^{-\lambda_a \gamma_{th}} - \lambda_a e^{-\lambda_b \gamma_{th}}}{\lambda_b - \lambda_a}. \quad (35)$$

We can substitute (27), (28) and (35) into (33) and similarly calculate the average bit energy consumption E_{a4} and the cooperative $gain_4$ in the DF with MRC as in (30), (31) in the case of DF without MRC.

C. Bit Energy Consumption and Cooperative Gain Analysis in DF

Fig. 6 shows the bit energy consumption with respect to $b \in [2, 4, 6, 8, 10]$ at a specific distance $d \in [5m, 25m, 50m, 75m, 100m]$. Results similar to those already identified in the fixed AF model are observed. At small S-D distances, the highest constellation should be preferred. The optimal constellation size gets smaller as the distance increases. It is noticed that MRC in the DF model provides only very limited improvement in energy efficiency compared with non-MRC. Only at points with large b and S-D distances, MRC curves show better energy efficiency over non-MRC. However, compared with Fig. 2 in the fixed AF, the bit energy consumption on these points has been significantly decreased in the selective DF model.

Very close performance of MRC and non-MRC in the DF models is also illustrated in the following figures. In Fig. 7, at a given b , the bit energy consumption is increasing as the S-D distance increases, due to the increasing system outage. But, the bit energy consumption when $b = 10$ at large distance has been significantly decreased in the selective DF models compared with Fig. 3 in the fixed AF.

Fig. 8 shows that both MRC and non-MRC in the DF mode almost achieve equal cooperative gain. At $b \in [2, 4, 6]$, the curves show almost flat gain less than 1, which advocates that the direct transmission is more energy efficient. At higher constellation sizes such as $b = 8$ or $b = 10$, the system can

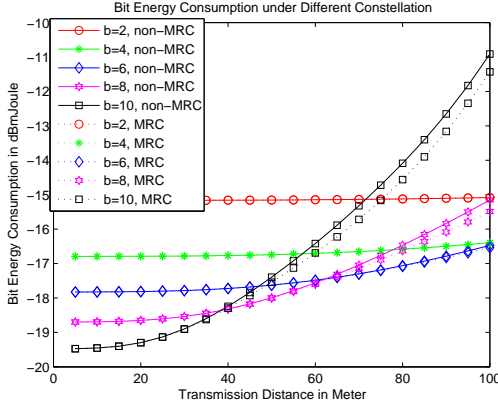


Fig. 7. Bit Energy Consumption vs S-D Distance in DF

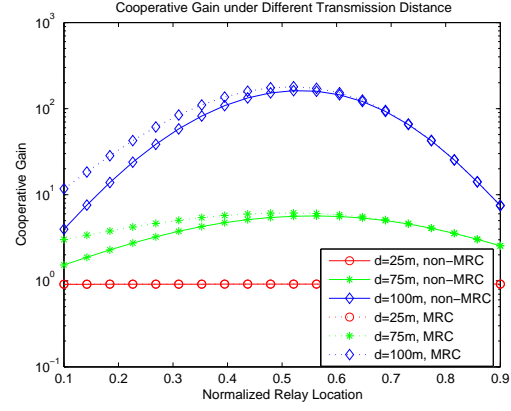


Fig. 9. Cooperative Gain vs Normalized Relay Location in DF

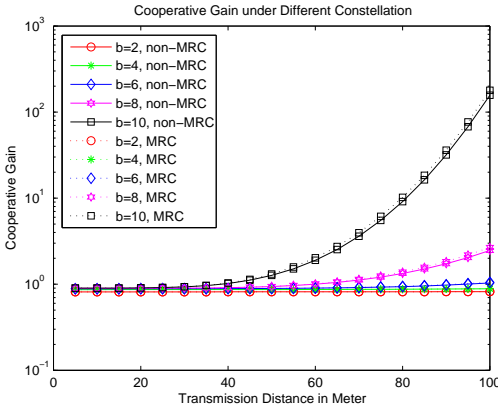


Fig. 8. Cooperative Gain vs S-D Distance in DF

achieve very high cooperative gains as the distance increases. Compared with Fig. 4, the DF models are more energy efficient than the AF models, especially at large b and S-D distance.

In Fig. 9, we have fixed $b = 10$. When the S-D distance is 25m in both MRC and non-MRC, changing the relay location doesn't affect the gain and direct transmission is more energy efficient because of $gain < 1$. At higher S-D distances such as 75m and 100m, we observe that the system benefits from the cooperative transmission and achieves relatively high cooperative gains. MRC provides higher gain when the relay is closer to the source. As the relay moves closer to the destination, both MRC and non-MRC models tend to achieve the same performance. The maximal cooperative gain is again achieved when the relay is located right in the middle.

V. CONCLUSION

We have considered fixed AF and selective DF models in a 3-node cooperative network. In each model, accurate energy expenditures which consider the circuit, transmission, and retransmission energies are formulated. The system reliability is derived from the link outage probabilities under a combined path-loss and Rayleigh fading channel. Both MRC and non-MRC decoding are performed at the destination in

AF and DF, and the optimal constellation sizes are identified. Several interesting results are observed: 1) in fixed AF, MRC outperforms non-MRC in terms of achieving less bit energy and higher cooperative gain; 2) in selective DF, MRC doesn't show much improvement on energy efficiency over non-MRC; 3) at small constellation sizes, direct transmission is more energy efficient in both models, while at large constellation sizes, the system can achieve significant cooperative gains as distance increases; 4) the optimal relay location is the middle between the source and the destination; 5) the selective DF is more energy efficient than the fixed AF, especially at large constellation size and transmission distance.

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